Fermilab

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Fermilab: Accelerator Complex for Neutrinos

Paul Derwent
IIEB Fermilab
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Fermilab Program Goals

Fermilab's goal is to construct & operate the foremost facility in the world for particle physics research utilizing intense beams.

- Neutrinos
  - MINOS+, NOvA @700 kW
  - LBNF @ multi-MW
  - SBN @ 10's kW
- Muons
  - Muon g-2 @ 17-25 kW
  - Mu2e @ 8-100 kW
- Longer term opportunities

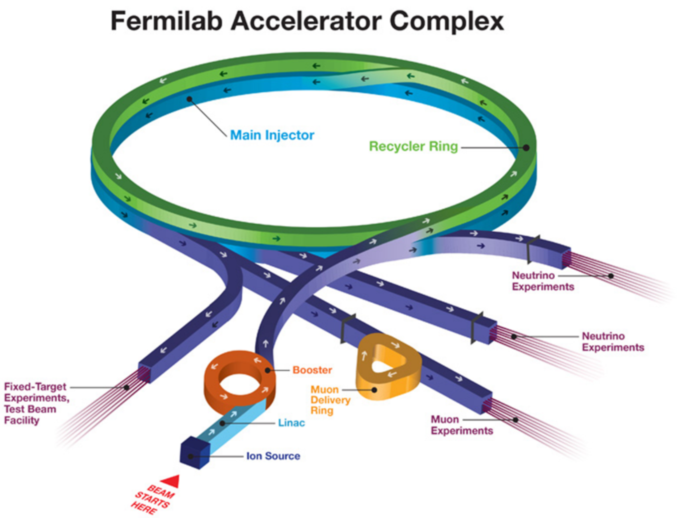
⇒ ***This requires more protons!***
(and this statement tends to be time invariant)

"Upgrade the Fermilab Proton Accelerator Complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIP-II) should proceed immediately, followed by construction, to provide proton beams of > 1 MW by the time of the first operation of the new long-baseline neutrino facility" – Recommendation 14, P5 report

The Fermilab Accelerator Complex Today

- The Fermilab complex delivers protons for neutrino production at both 8 and 120 GeV, with a present capability*:
  - Booster: 4.2×10^{12} protons @ 8 GeV @ 7.5 Hz = 40 kW
  - MI: 2.7×10^{13} protons @ 120 GeV @ 0.75 Hz = 390 kW

- Present limitations
  - Booster pulses per second
    - The Booster magnet/power supply system operates at 15 Hz
    - However the RF system is only capable of operating at ~7.5 Hz
  - Booster protons per pulse
    - Limited by space-charge forces at Booster injection, i.e. the linac energy
  - Target systems capacity
    - Limited to ~700 kW by a large number of factors



* As currently configured

Strategy for the next ~10 years
Proton Improvement Plan (PIP)

The near-term goal is to double the Booster beam repetition rate to 15 Hz, while addressing reliability concerns

- Required for simultaneous operations of NOvA, g-2, Mu2e, SBN
- 700 kW to NOvA: 4.9e13 @ 120 GeV @ 0.75 Hz

- Design Criteria
  - 15 Hz beam operations at 4.2×10^{12} protons per pulse (80 kW)
  - Linac/Booster availability > 85%
  - Residual activation at acceptable levels
  - Useful operating life for the Linac through 2023 and the Booster through 2030
- Scope
  - 15 Hz Capability:
    - RF upgrades, cavity refurbishment
    - Power and water distribution
  - Reliability: >85% uptime, reduce operational risk
    - Drift Tube Linac RF replacement ⇒200 MHz klystrons/modulators
    - Additional Booster RF cavities
    - Power and water distribution
  - Beam Quality and Losses: RFQ, dampers, collimators/absorbers
    - To maintain activation at current levels or lower
- Execute over the years 2011 – 2018

Strategy for the next ~10 years
Proton Improvement Plan-II (PIP-II)

The longer-term goal is to increase the beam power delivered from the Main Injector by an additional 50% and to provide increased beam power to the 8 GeV program, while providing a platform for the future

- Strategy
  - Increase the Booster per pulse intensity by 50%
    - Requires increase in injection energy to ~800 MeV
  - Modest modifications to Booster/Recycler/MI
- Design Criteria
  - Deliver 1.2 MW of beam power at 120 GeV, approaching 1 MW down to 60 GeV, at the start of LBNF operations
  - Support the current 8 GeV program, including Mu2e, g-2, and the suite of short-baseline neutrino experiments
  - Provide an upgrade path for Mu2e
  - Provide a platform for extension of beam power to LBNF to >2 MW
  - Provide a platform for extension of capability to high duty factor/higher beam power operations
  - At an affordable cost to DOE
- Execute over 2015 – 2023

PIP-II

- *"The central element is a new 800 MeV superconducting linac operated at low duty factor but constructed to be capable of continuous operation" P5 report, p. 47*

- PIP-II plans to build an 800 MeV superconducting pulsed linac, extendible to support multi-MW operations to LBNF and constructed of continuous wave (CW) capable components
  - Builds on significant existing infrastructure
  - Capitalizes on major investment in superconducting rf technologies
  - Eliminates significant operational risks inherent in existing linac
  - Siting consistent with eventual replacement of the Booster as the source of protons for injection into Main Injector
- Whitepaper available at

  projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1232

At completion of PIP-II the existing 400 MeV linac will be removed from service

Performance Goals

Performance Parameter	PIP	PIP-II	
Linac Beam Energy	400	800	MeV
Linac Beam Current	25	2	mA
Linac Beam Pulse Length	0.03	0.5	msec
Linac Pulse Repetition Rate	15	20	Hz
Linac Beam Power to Booster	4	13	kW
Linac Beam Power Capability (@>10% Duty Factor)	4	~200	kW
Mu2e Beam Power	8	>100	kW
Booster Protons per Pulse	4.2×10^{12}	6.4×10^{12}	
Booster Pulse Repetition Rate	15	20	Hz
Booster Beam Power @ 8 GeV	80	160	kW
Beam Power to 8 GeV Program (max)	32	80	kW
Main Injector Protons per Pulse	4.9×10^{13}	7.5×10^{13}	
Main Injector Cycle Time @ 120 GeV	1.33	1.2	sec
LBNF Beam Power @ 120 GeV	0.7	1.2*	MW
LBNF Upgrade Potential @ 60-120 GeV	NA	>2	MW

*LBNF beam power can be maintained down to ~60 GeV, then scales down with beam energy

PIP-II Status and Strategy

- PIP-II is in the development phase and is not yet recognized as a formal DOE project
  - However, PIP-II has received very strong support from P5, DOE/OHEP, and the Fermilab director
  - Expect formalization of project status (CD-0) in the next year, with a ~5-year construction period, starting in the current decade
- Goals for FY2015: R&D to retire risk in advance of CD-3
  - Receive RFQ (from LBNL) and initiate commissioning at PXIE
  - Keep HWR and SSR1 fabrication on schedule
  - Release PIP-II Reference Design Report
  - Develop deliverables strategy with India (and Europe)
  - Update current cost estimate as necessary
  - Start developing a resource loaded schedule
  - Support DOE/OHEP in development of Mission Needs Statement
  - Establish PIP-II Office

Timescales for Beam Delivery

PIP

- 2015: 3.3e13 @ 120 GeV @ 0.75 Hz = 475 kW
  - 1.25 Hz to BNB for Short Baseline Program
  - ~10% reduction to support SY120 program
- 15 Hz Booster Operation: Enables 700 kW NuMI operation
  - **Fall 2016**: 20 cavities to refurbish, need 17 for minimal operation, 11 complete at this time
  - Enough cycles to provide requested beam to the LBN program (NuMI), the SBN program (BNB), and the Muon Program
- Reliability and Beam Loss programs will continue ~2018

PIP-II

- 2015: PXIE and SRF R&D, Project Start
- 2019: Construction Start
- 2023: Completion:
  - overlap Civil tie in to Booster with LBNF tie in to MI
  - commission new linac with beam w/o interrupting NuMI program
  - Commission Booster, Recycler, and Main Injector at higher intensity

Power and Beam Characteristics

$P = 1.6 \, {}^{EN}/_{t}$ kW

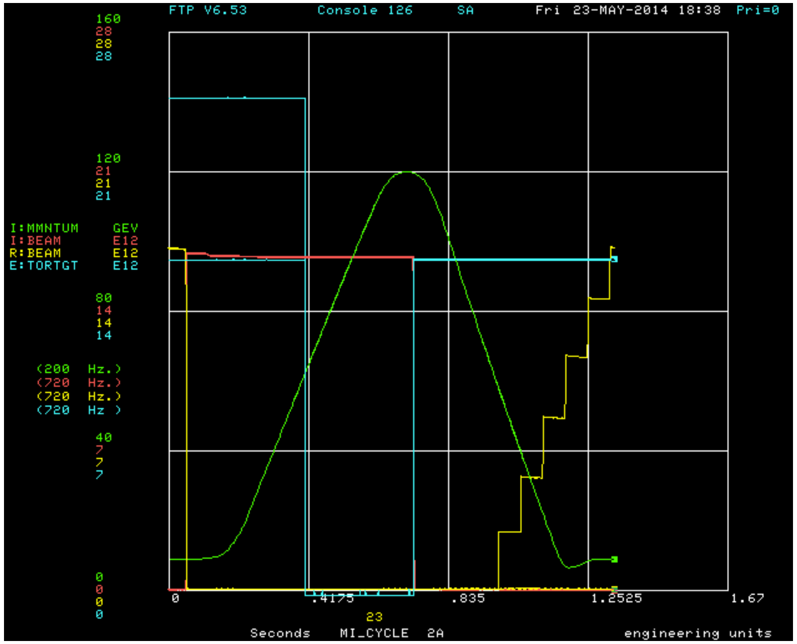
E in GeV

N in 1e13

t in seconds

- PIP-II : 1.2 MW
  - 7.5e13 @ 120 GeV every 1.2 seconds
  - Booster operating at 20 Hz: cycles multiples of 50 msec
  - Slip Stacking: 12 cycles = 0.6 sec
  - MI Ramp: 240 GeV/second + parabolas + reset

Energy (GeV)	Intensity(e13)	Cycle Time (sec)	Power (kW)
120	7.5	1.2	1200
110	7.5	1.1	1200
100	7.5	1.05	1143
90	7.5	0.95	1137
80	7.5	0.9	1067
70	7.5	0.8	1050
60	7.5	0.7	1029
50	7.5	0.65	923
40	7.5	0.6	800
30	7.5	0.6	600



Future Directions beyond 1 MW PIP-II program

- The strategy for next step(s) beyond PIP-II will be developed in consideration of the following:
  - Slip-stacking in the Recycler may not be possible at intensities beyond PIP-II
  - The Booster cannot be upgraded to support intensities beyond $\sim 7\times 10^{12}$ ppp, no matter what the injection energy
  - A new 8 GeV source is necessary
  - Models:
    - 1.5-2 GeV linac + conventional Rapid Cycling Synchrotron
    - ‘supersmart RCS’ that mitigates beam losses (R&D into space charge effects)
    - ‘brute force’ but cost effective 6-8 GeV linac (R&D into performance and cost)
- The strategy will be determined on the basis of R&D progress and physics programmatic choices

Example: 2+ MW @ 60-120 GeV

- 2.4 MW requires 1.5×10^{14} protons from Main Injector every 1.2 s @ 120 GeV
  - Every 0.6 sec @ 60 GeV
- Accumulation requires either:
  - Box-car stack (in Recycler) six batches of 2.5×10^{13} protons in ≤ 0.6 sec
    - ⇒>10 Hz rep-rate RCS
  - Or inject a long (linac) pulse containing 1.5×10^{14} protons directly into Main Injector
  - Strategy TBD

Possible Parameters for post-PIP-II Complex

Proton Source	**RCS**	**Linac**	
Particle Type	p	H-	GeV
Beam Kinetic Energy	8.0	8.0	GeV
Protons per Pulse	2.6×10^{13}	1.5×10^{14}	
Beam Pulse Length	0.0016	10	msec
Pulse Repetition Rate	20	20	Hz
Pulses to Recycler	6	NA	
Pulses to Main Injector	NA	1	
Beam Power at 8 GeV (Total)	660	3960	kW
Beam Power to Main Injector*	160/280	160/280	kW
Beam Power Available for 8 GeV Program*	500/380	3800/3680	kW
Main Injector			
Beam Kinetic Energy*	120/60	120/60	GeV
Main Injector Protons per Pulse	1.5×10^{14}	1.5×10^{14}	
Main Injector Cycle Time*	1.2/0.7	1.2/0.7	sec
LBNF Beam Power*	2.4/2.1	2.4/2.1	MW

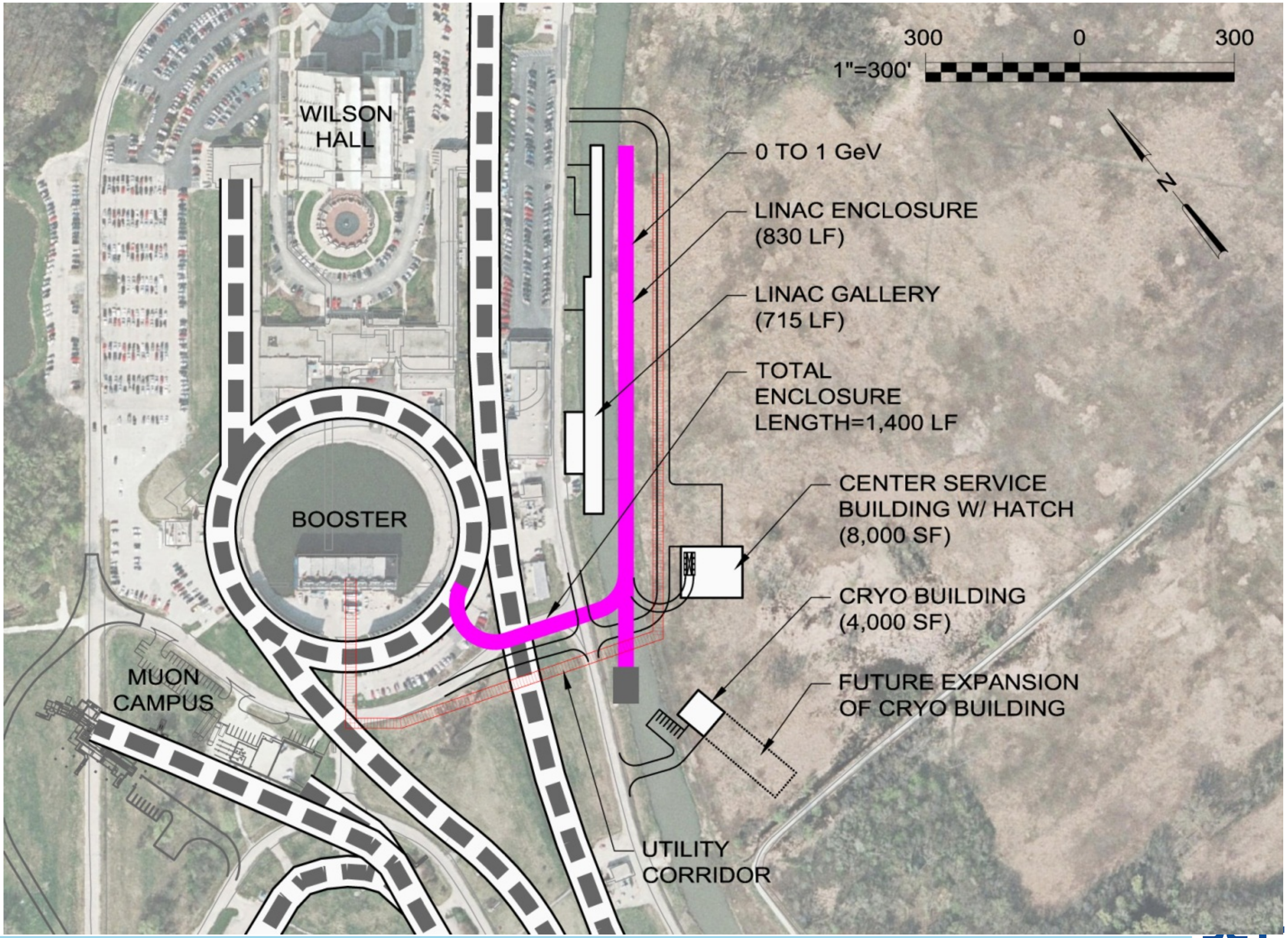
*First number refers to 120 GeV MI operations; second to 60 GeV

Summary

- PIP and PIP-II have been developed as steps in establishing a world-leading facility for particle physics research based on intense beams, at Fermilab
  – LBNF >1 MW at startup
  – 8 GeV program >40 kW coincident with LBNF
- PIP-II retains flexibility to eventually realize the full potential of the Fermilab complex
  – multi-MW to LBNF
  – multi-MW to SBN program
  – High power/high duty factor operations at 0.8-3 GeV
- Capitalizing on these longer term opportunities will require accelerator R&D with advances in SRF, space-charge and beam loss mitigation, and high power targets

Backups

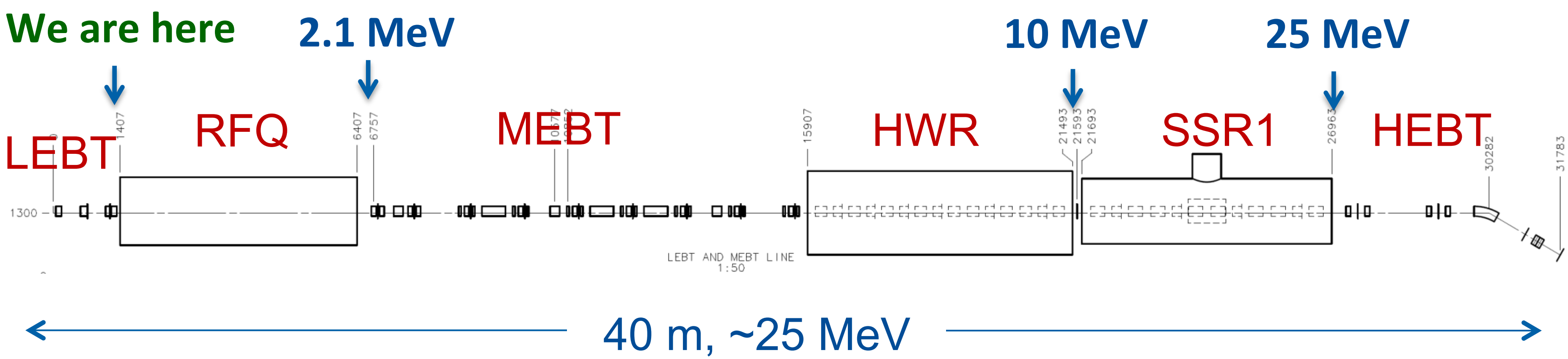
PIP-II Site Layout (provisional)



PIP-II R&D Strategy

- Goal is to mitigate risk: Technical/cost/schedule
- Technical Risks
  - Front End (PXIE)
    - Complete systems test: Ion Source through SSR1 (25 MeV)
  - Operations of (high Q_0) superconducting linac in pulsed mode
    - Primary issue is resonance control in cavities
    - Generally applicable to next generation SC linacs
    - Task force defining options
    - Options evaluated at PXIE
- Cost Risks
  - Superconducting RF
    - Cavities, cryomodules, RF sources represent 46% of construction costs
- Goal: Be prepared for a construction start in 2018-19

PXIE



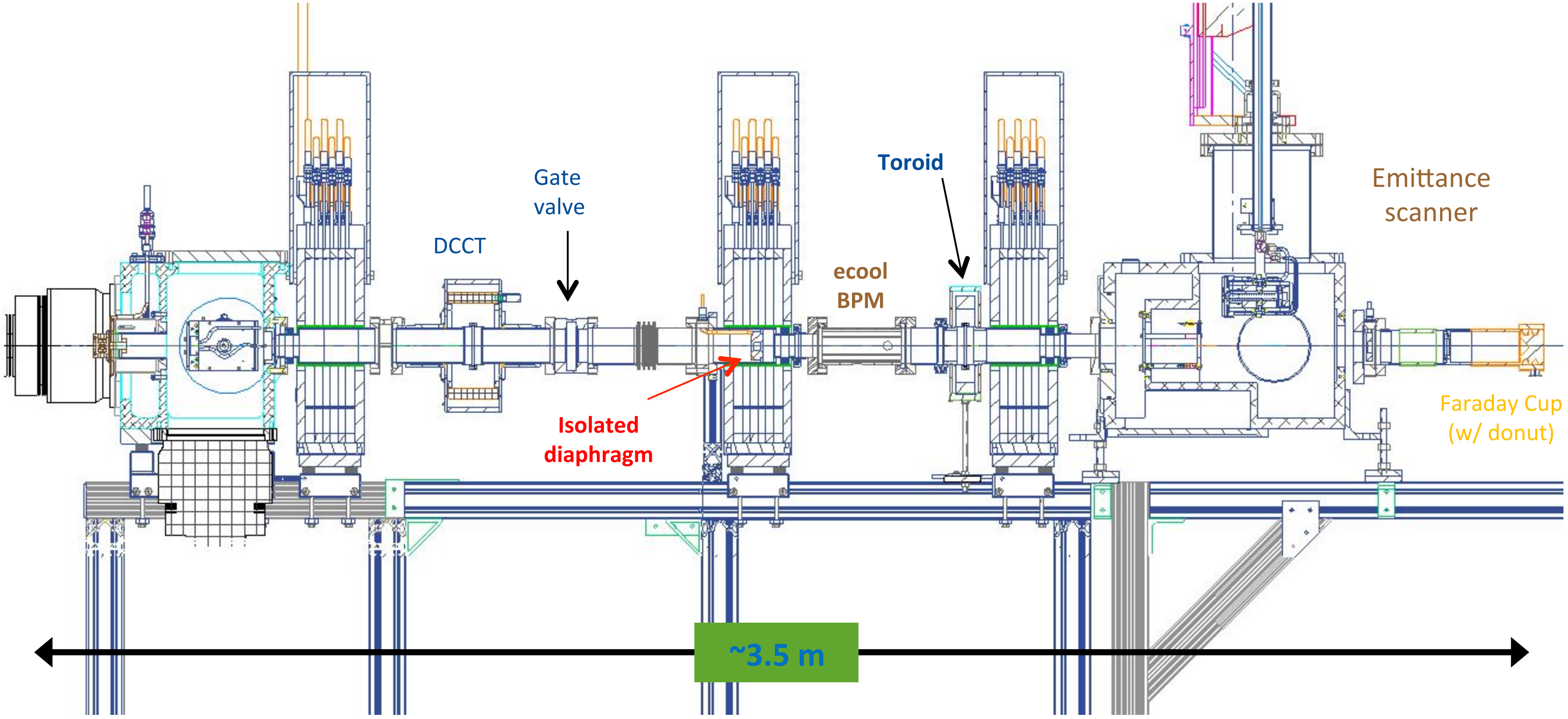
PXIE will address the address/measure the following:

- LEBT pre-chopping
- Vacuum management in the LEBT/RFQ region
- Validation of chopper performance
- Bunch extinction
- MEBT beam absorber
- MEBT vacuum management
- Operation of HWR in close proximity to 10 kW absorber
- Operation of SSR with beam, including resonance control
- Emittance preservation and beam halo formation through the front end

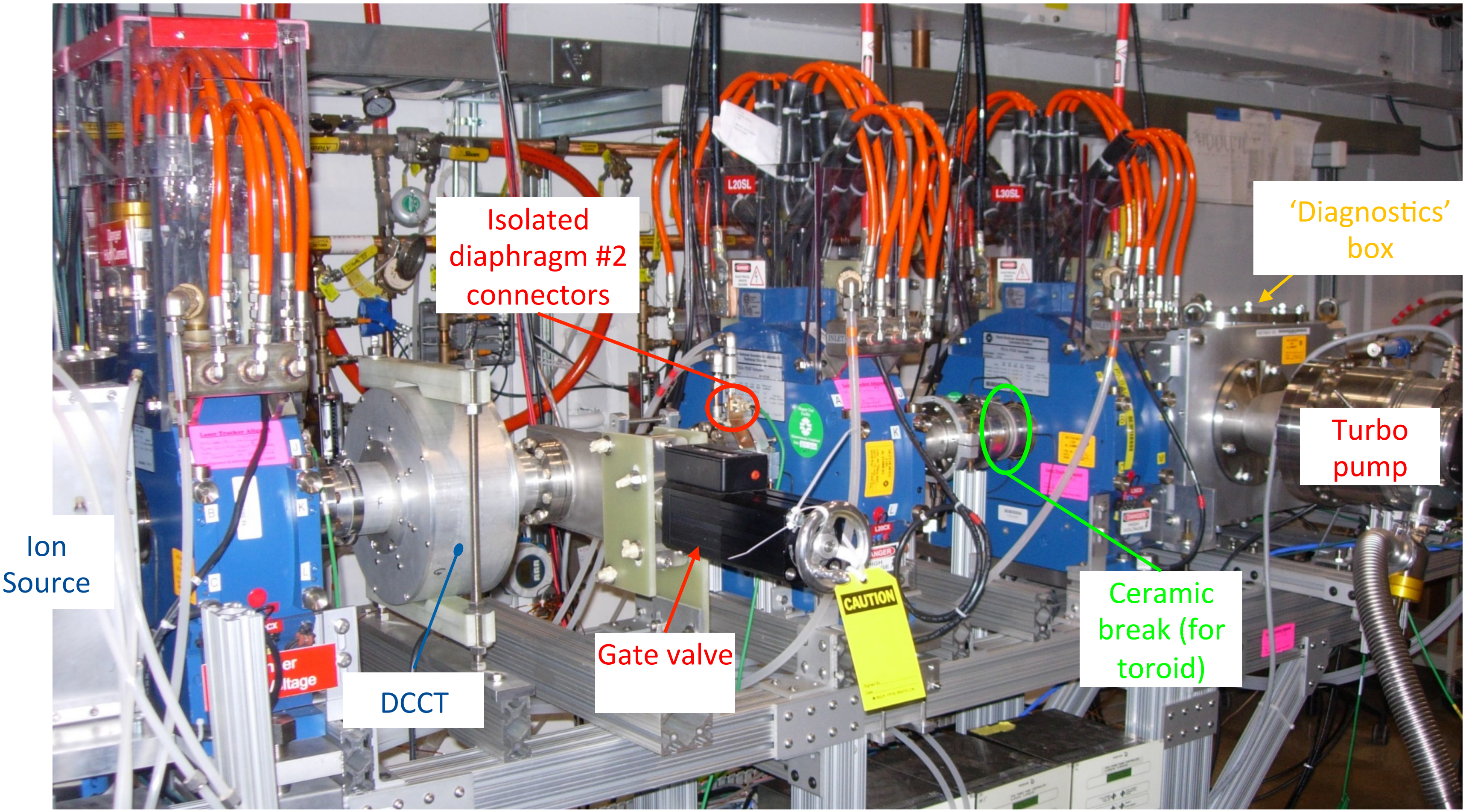
Collaborators
ANL: HWR
LBNL:LEBT, RFQ
SNS: LEBT
BARC: MEBT, SSR1

Current Configuration (August 2014)

- All solenoids installed
  - + ecool BPM as ‘clearing’ electrode until chopper is ready
  - Emittance scanner at ~location of RFQ entrance

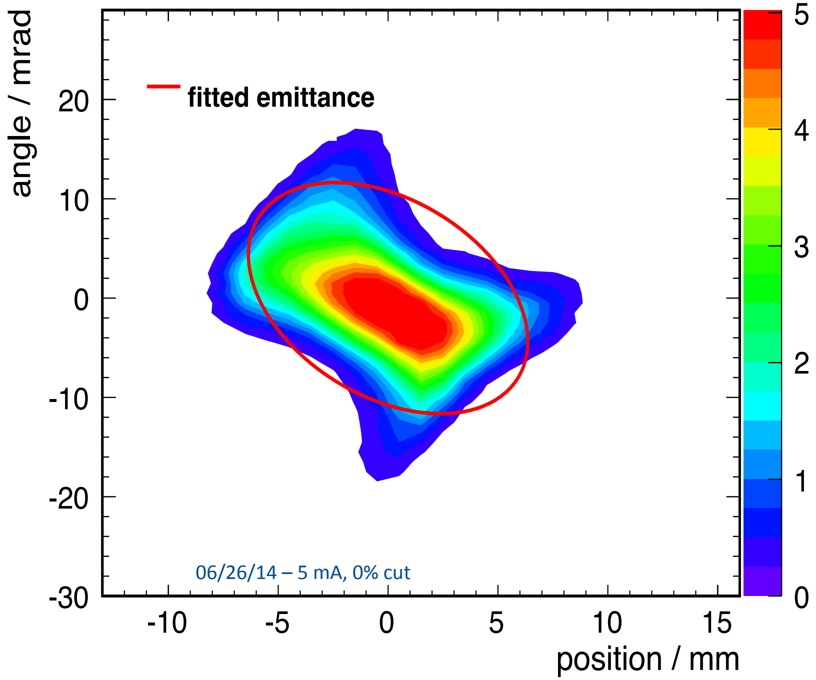


Current Configuration (August 2014)

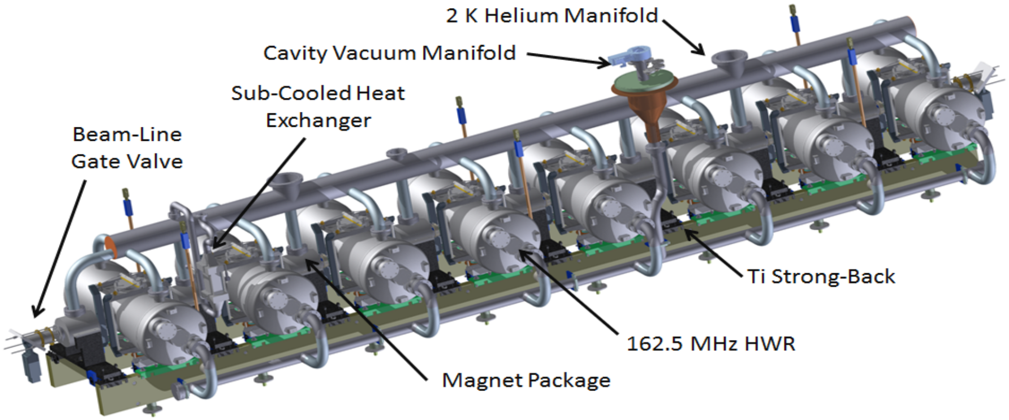


Emittance measurements

- Carried out emittance scans for various conditions
  - Analyses underway
  - Preliminary calculations of the emittance for beam settings similar to those from 6/6/14 (i.e. donut data set) are ~30% higher
  - core shape vs tail contribution

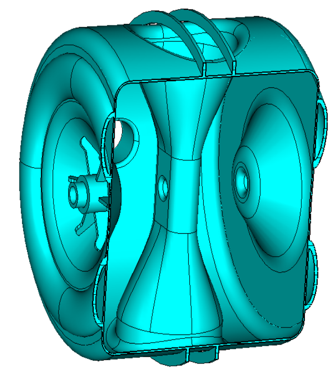


SRF R&D

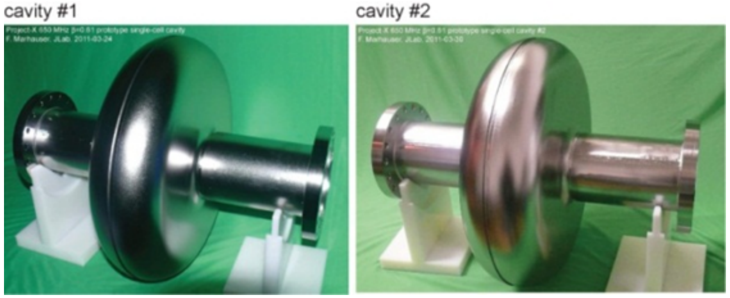


HWR

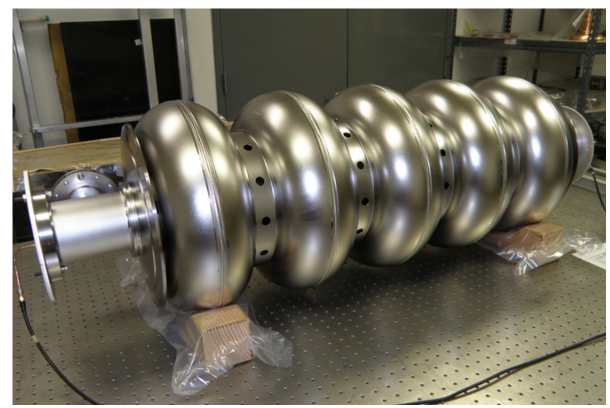
SSR1



SSR2

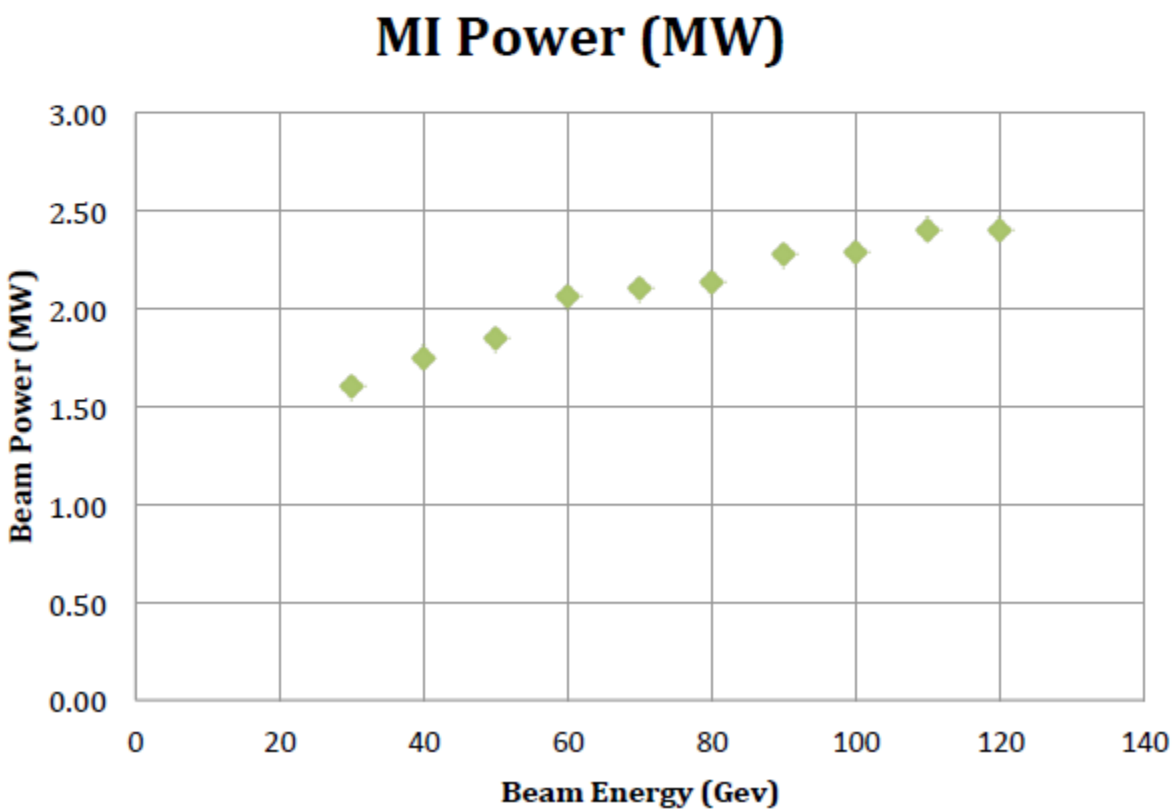


LB650



HB650

Possible Parameters for post-PIP-II Complex



PIP-II Collaboration

- Collaboration MOUs for the RD&D phase (through CD-2) :

National		IIFC
ANL	ORNL/SNS	BARC/Mumbai
BNL	PNNL	IUAC/Delhi
Cornell	UTenn	RRCAT/Indore
Fermilab	TJNAF	VECC/Kolkata
LBNL	SLAC	
MSU	ILC/ART	
NCSU		

- Ongoing contacts with CERN (SPL), RAL/FETS (UK), ESS (Sweden), RISP (Korea), China/ADS
- Annual Collaboration Meeting (June 3-4 at Fermilab)

  https://indico.fnal.gov/conferenceDisplay.py?confId=8365